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ANOMALOUS DISPERSION AND THE PUMPING OF FAR-INFRARED (FIR) LASERS

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16. Abstract

It is shown that the anomalous dispersion at the pump transition in molecular far-infrared lasers (FIR) can lead to sizable focusing and defocusing effects. Criteria for beam spreading and trapping are considered with CH_3F as an example.

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Introduction

The dependence on intensity of the real susceptibility can lead to significant increases or reductions in the index of refraction near an atomic or molecular transition. These effects are most prevalent in the saturated regime. Javan and Kelley[1] have given expressions for the index change due to this effect for both homogeneously broadened, as well as Doppler-broadened, transitions. Depending on whether the presence of an intense beam increases or decreases the local index of refraction, focusing or defocusing of the beam may occur. When the index change is sufficiently high that the diffraction angle of the beam is below the critical angle for the index change, the beam becomes trapped.

The index at any point in the medium can be expressed as some constant value plus a perturbing term,

$$n(r) = n_o + \delta n(r) \quad . \tag{1}$$

For Doppler broadening, the profile is approximated by a Lorentzian line-shape function to circumvent the difficulties associated with the convolution of a Gaussian and Lorentzian. For homogeneous broadening,

$$\delta n(r) = \frac{2\pi \chi''(\nu_o)(\nu - \nu_o)}{n_o \Delta\nu_n \left[1 + \dfrac{(\nu - \nu_o)^2}{\Delta\nu_h^{\,2}} + \dfrac{\mu_{ij}^{\,2} \, |E(r)|^2 \, T^1}{\hbar^2 \Delta\nu_h} \right]} \quad . \tag{2}$$

where μ_{ij} is the dipole matrix element for the transition from $i \longrightarrow j$, $|E(r)|^2$ is $2/c\epsilon_0$ times the intensity, $\Delta\nu_h$ is the homogeneous line width, ν_0 is the line-center frequency, $\chi(\nu_0)$ is the peak field independent imaginary susceptibility, and T^1 is a characteristic time of the levels. In [1], it is shown that, when the intensity is well above saturation, the index change asymptotically reaches a maximum value,

$$\delta n_{max} = \frac{-2\pi\chi''(\nu_o)(\nu-\nu_o)}{\Delta\nu_h\left[1+\left[\frac{(\nu-\nu_o)}{\Delta\nu_h}\right]^2\right]} \qquad (3)$$

In the case of Doppler broadening with an associated line width, $\Delta\nu_D$, (2) is modified to

$$\delta n^{(D)}_{(r)} = \frac{2\pi\chi''(\nu_o)(\nu-\nu_o)\left(\frac{1}{\Delta\nu_D}+\frac{1}{\Delta\nu_h}\right)\Delta\nu_h}{n_o\Delta\nu_D\left\{\frac{(\nu-\nu_o)^2}{\Delta\nu_D{}^2}+\left(1+\frac{\Delta\nu_n}{\Delta\nu_D}\left[1+\frac{\mu_{ij}^2\,|E(r)|^2\,T^1}{\hbar^2\,\Delta\nu_h}\right]^{1/2}\right)^2\right\}} \qquad (4)$$

This reaches a maximum value above saturation given by

$$\delta n^{(D)}_{max} = \frac{2\pi\chi''(\nu_o)(\nu-\nu_o)\left(\frac{1}{\Delta\nu_D}+\frac{1}{\Delta\nu_h}\right)\Delta\nu_h}{n_o\Delta\nu_D\left[\frac{(\nu-\nu_o)^2}{\Delta\nu_D{}^2}+\left(1+\frac{\Delta\nu_n}{\Delta\nu_D}\right)^2\right]} \qquad (5)$$

For a homogeneously broadened line, the maximum index change occurs for

$$(\nu-\nu_o) = \Delta\nu_h\;, \qquad (6)$$

and, for an inhomogeneously broadened line, at

$$(\nu - \nu_o) = \Delta\nu_D + \Delta\nu_h \quad . \tag{7}$$

Far infrared (FIR) lasers fall into two categories. Most CW lasers are operated in the Doppler-broadened regime, whereas high-power pulsed systems are operated in the pressure-broadened region. Because these lasers are optically pumped by CO_2 lasers, efficient use of pump power is crucial to optimized performance.

Koepf and McAvoy[2] have dealt with the problem of best utilizing pump power through various resonator configurations. However, this treatment and others have not dealt with the effects of index change and its associated effects on the CO_2 pump beam. The well-documented CH_3F laser will be used to demonstrate the requirement that these spatial effects be considered. CH_3F has been operated in CW and pulsed modes and therefore lends itself to the analysis. However, note that it is not by any means a gas that exhibits the largest index effects. Other FIR laser gases have much higher absorption coefficients and associated nonlinearities.

The relevant parameters for CH_3F are:

$$\Delta\nu_h = 40\ \mathrm{MH_z/torr} \ ,$$

$$\Delta\nu_D = 67\ \mathrm{MH_z} \ ,$$

$$(\nu - \nu_o) = -40\ \mathrm{MH_z} \ .$$

where $(\nu - \nu_0)$ is an estimated value from the CO_2 9μ P(20) line center to the molecular line center. In equations 3 and 5, $\chi''(\nu_0)$ can be replaced by

$$\chi''(\nu_0) = \frac{\lambda \gamma_{max} n_o^2}{2\pi} \quad , \tag{8}$$

where γ_{max} is the peak line-center absorption coefficient, and λ is the wavelength. This has a value of about 5 m^{-1} at 1 torr for CH_3F. For CO_2 intensities above saturation can be estimated by using the CH_3F data ($I_S = 2.3 \times 10^2 W/cm^2 \ torr^2$). At 1.25 torr, the line is Doppler-broadened and leads to an index change of

$$\delta n^{(D)} \approx {}^{-}(2 \times 10^{-5}) \ n_o \ .$$

When the pressure is 2 torr, the line is homogeneously broadened, and the index change is given by

$$\delta n \cong {}^{-}(10^{-4}) \ n_o = n_o \delta \ .$$

Therefore, in the region of an intense beam, the index is given by

$$n = n_o(1 - \delta) \ , \tag{9}$$

where

$$\delta \cong 10^{-4} \ .$$

Beam Optics

The basic problem of what happens to the pump beam can be dealt with using ray optics. Since most FIR lasers are pumped through a coupling hole, the pump beam is usually focused to a 1 to 3 mm waist on entering the resonator.[2] For a 20-watt CO_2 laser, this produces intensities on the order of megawatts. These levels are well above saturation. At the waist point, the beam will spread due to diffraction with an angle,

$$\theta_D \approx \frac{\lambda}{\pi n_o \omega_o} \quad , \tag{10}$$

where ω_o is the input radius. The beam behavior can be analyzed by examining the outermost ray (see Figure 1).

Referring to Figure 1,

$$\begin{aligned} n_o(1-\delta)\cos\theta_D &= n_o \cos\phi \quad , \\ (-1+\delta) &\cong -1 + \frac{\phi^2}{2} \quad , \\ \phi &\approx \sqrt{2\delta} \quad . \end{aligned} \tag{11}$$

For a typical coupling hole which is 3.0 mm in diameter, $\theta_D = 2 \times 10^{-3}$ rad. Moreover, the new beam divergence angle, ϕ, is 1.4×10^{-2} rad. This is an order of magnitude larger than θ_D.

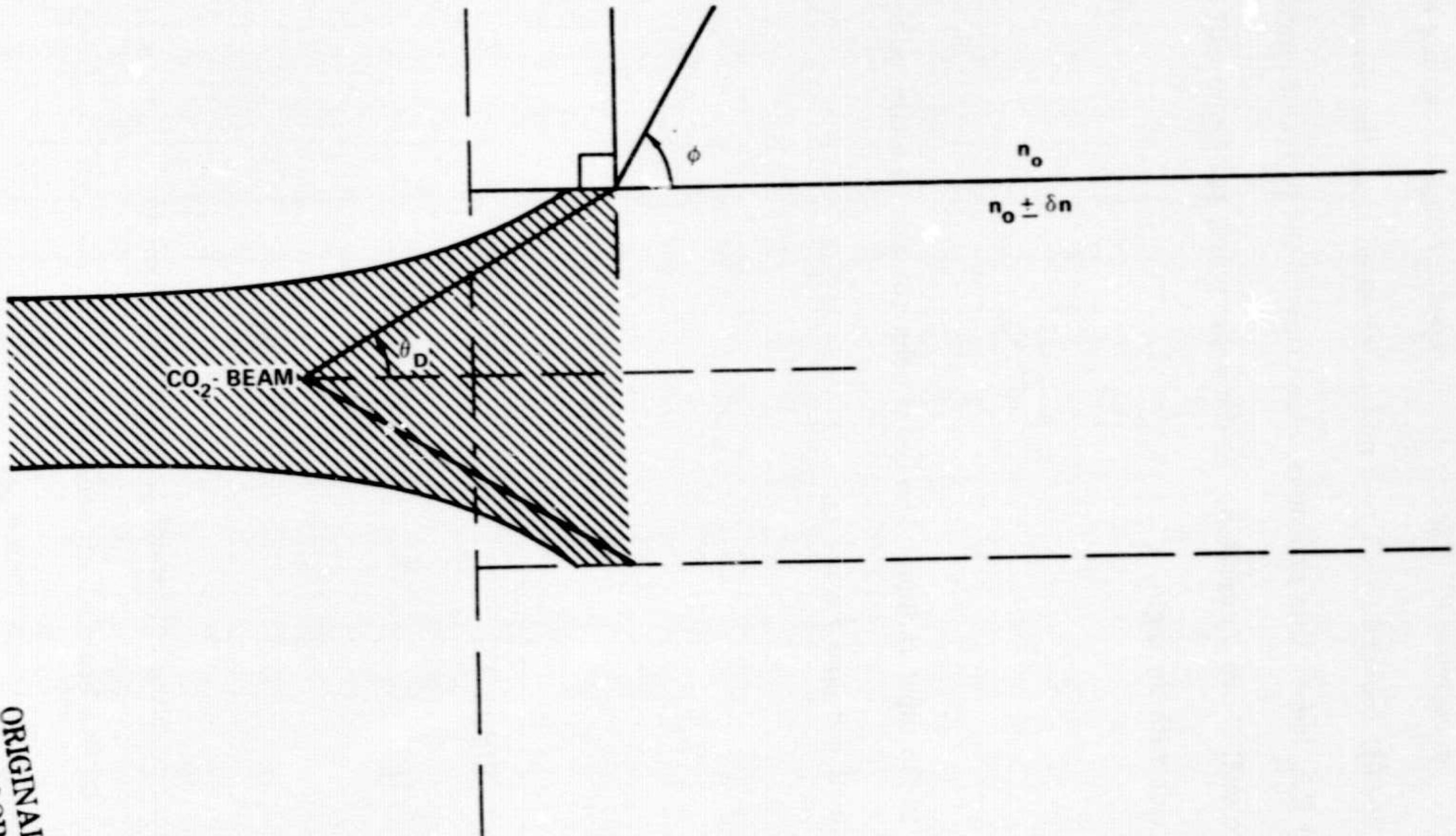

Figure 1. Defocusing Caused by Index Change

When the CO_2 line is higher in frequency than the molecular line center, δn is positive and focusing or trapping of the pump power takes place. The criterion for this is that the diffraction angle, θ_D, is smaller than the critical angle. This means that

$$\cos\theta_D \geqslant \frac{1}{1+\delta} \quad . \tag{12}$$

or

$$\delta > \frac{\lambda^2}{2\pi^2 n_o^{\,2} \omega_o^{\,2}} \quad . \tag{13}$$

When trapping occurs, the pump beam is well-confined and can be used efficiently.

In the case of beam defocusing, the beam size at a point Z in the laser can be estimated by

$$\omega^1 = \omega_o + Z\sqrt{2\delta} \quad . \tag{14}$$

This is equivalent to defocusing at a waist by a diverging lens of focal length

$$f \equiv \frac{\omega_o}{\sqrt{2\delta}} \quad . \tag{15}$$

Conclusions

The efficient utilization of CO_2 laser power for pumping FIR lasers is crucial to optimizing their conversion efficiencies. Because pumping large cross-sectional areas is desirable, it appears that a well-defined pump beam guided by the proper resonator geometry is the most promising. The effects described here indicate that caution must be exercised when laser tube diameters are chosen so that the pump beam is not interfered with when defocusing occurs. In conclusion, it appears that FIR lasers that exhibit high gains and are pumped on the far side of the absorption profile (resulting in trapping) would be the best candidates for pump-resonator optimization because the beam becomes well-defined and tractable.

<u>References</u>

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[2] Koepf, G. A., and N. McAvoy, "Design Criteria for FIR Waveguide Laser Cavities," IEEE J. Quantum Electronics, QE-13(6), June 1977, pp. 418-421.